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Power sector renewable energy integration for expanding access to electricity in sub-Saharan Africa

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ABSTRACT

A looming energy supply crisis in sub-Saharan Africa (SSA) raises concerns about a long-lasting energy shortage. This energy crisis is expected to persist for an indefinite period in the region unless immediate actions are taken to reverse the trend. Although global aspiration to reduce greenhouse gas (GHG) emissions into the atmosphere is high, such desire is low in SSA. Regional stakeholders are more worried about increasing power generation capacity to enhance better access to different sorts of development. To progress in line with advanced patterns of energy development globally, to increase the availability of electrical energy and to sustain emissions reductions, exploitation of local renewable energy (RE) resources is inevitable. Consequently, this paper presents a comprehensive review of RE integration for expanding access to electricity in SSA. The review covers the sustainability of RE resources in SSA, the regional status of RE applications and the necessity of RE power generation integration planning from a management aspect. Finally, the benefits of RE integration into the power sector of SSA and some conceptual challenges affecting its integration in the region are highlighted.

Contents

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1. Introduction

Most developing countries envision increased development in the future. However, the attainment of such status requires an enormous level of energy consumption. Modern conventional power generation infrastructures and some energy consumption processes release greenhouse gas (GHG) emissions unaltered into the surrounding atmosphere. GHGs are principally dispensed from fossil-based energy resources commonly used for large-scale electricity generation. Environmentalists have cultivated a close relationship between RE and sustainable development [1–4]. Most developing countries cannot afford to depend entirely on oil and gas for their electricity demands, especially today with fluctuating fossil fuel prices in the global market. With ongoing regular energy shortages in developing countries, a rethink of integrated energy resource planning to increase access to electrical energy, especially for social, environmental and economic growth, is unavoidable. Today, before a resource can be considered for electrical energy production, some specific requirements must be satisfied. These include cost, environmental pollution, technological robustness, fuel supply stability and energy supply efficiency. In this respect, it can be concluded that renewable energy sources (RESs) meet all the basic requirements for both current and future sustainable energy supply scenarios as revealed in Fig. 1.

The integration of RE into the power sector is not a new concept in any part of the world. It has been a continuously and progressively changing idea, with RE regarded as having a substantial positive role to play, especially in expanding access to energy in regions of energy shortages. The integration of RE into the power sector could be considered more worthwhile in regions where there is a large quantity of sustainable and renewable resources available and where there is a proper understanding of the utilisation technologies. The use of RE to supplement or to replace fossil fuels provides many benefits to developing countries [6–9]. SSA has many isolated rural settlements and promoting RE technologies in these less densely populated areas could facilitate increased energy access to households [10–15], with resulting impacts on economic, environmental and social status [16]. As economic development depends on the energy systems of a country [17], there is a social and moral justification for enhancing the energy resources of all countries. On the one hand, in developing countries, there is a need to increase the level of the available amount of energy supply, whereas on the other hand, there is global interest in carbon emission reduction. To strategically realise the current demand to sustain a low carbon electricity sector in developing countries, many researchers and international energy stakeholders anticipate the integration of RE into the power sector.

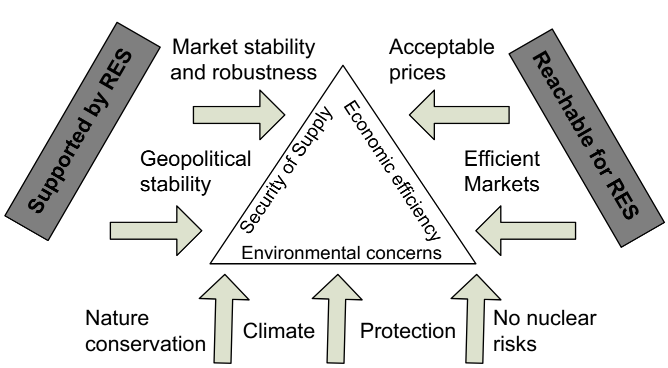

Fig. 1. An energy triangle showing all essential requirements of a sustainable energy supply system can be fulfilled by RES at present and in the future [5].

Power sector RE integration could be achieved through integrated green energy resource planning (IGERP), with potential impacts on energy delivery and consumption systems. IGERP is a synchronised planning mechanism for different RE resources. An integrated resource planning (IRP) approach involves a change in the mix of end-use electricity using equipment at the demand side and a change in the total electricity generation, installed capacity, fuel mix, technology mix and environmental emissions at the supply side [18]. Power sector reform is an ongoing phenomenon in some developing countries, especially in SSA, because several reform strategies introduced in the past have yet to exhibit some expected positive impacts. In addition, adequate planning of energy resources incorporating RES have not been translated into effective measures in a regional framework for energy in SSA. Realistically, modern RE exploitation and development in SSA is lagging behind many any other regions in the world due to the following reasons:

- Limited capital investment
- Lack of technological knowledge on RE development
- Constricted power generation planning
- Deficient electricity supply resulting from frequent power systems failure and unreliable equipment
- Low rate of electrification in the region
- High cost of electrical energy generation
- High transmission losses

These constricting factors have adversely affected any effort to expand access to electricity in the region. Approximately 31% of people have access to electricity in SSA, with about a 14% electrification rate in the rural areas [19]. Table 1 shows the electrification status of different countries in SSA and in the northern axis of Africa. Apart from Ghana and Mauritius, the electrification rate by percentage in other countries is quite low, below 50% on average. In Fig. 2, two possible scenarios are shown regarding the electricity generation capacity of SSA. In the first case, it is obvious that electricity generation in SSA (excluding South Africa) has the lowest electricity generation capacity among the developing regions of the world. The trend in capacity has been frozen at a point close to 50 MW per million people for more than 18 years. When South Africa is included in the analysis, the potential of the region increases, and the capacity is slightly better than that in South Asia between 1990 and 1997. In 2008, South Africa alone had a share of 56.1% of the 92.3 MW per million people of the total installed capacity of the region [20]. The prevailing trend changed from 2002 to 2008, with the capacity of SSA falling below that of South Asia, even with the addition of South Africa.

A review of the current use of RE in SSA is necessary to examine the possibility of integrating RE into the power sector of the countries in the region. Section 1 provided an introduction to the subject. In Section 2, a short review on power sector RE integration is presented. Section 3 discusses the various types of renewable resources available in SSA. Section 4 presents a brief discussion of the current status of RE exploitation in the region. RE generation planning and management strategies are briefly highlighted in

Table 1
Access to electricity in Africa in 2005 [21–23].

Country	Electrification rate (%)	Population without electricity (million)	Population with electricity (million)
Angola	15	13.5	2.4
Benin	22	6.5	1.8
Botswana	38.5	1.1	0.7
Burkina Faso	7	12.4	0.9
Cameroon	47	8.7	7.7
Congo	19.5	3.2	0.8
Dem. Rep. Congo	5.8	53.8	3.3
Cote d'Ivore	50	9.1	9.1
Eritrea	20.2	3.5	0.9
Ethiopia	15	60.8	10.7
Gabon	47.9	0.7	0.7
Ghana	49.2	11.3	10.9
Kenya	14	29.4	4.8
Lesotho	11	1.9	0.2
Madagascar	15	15.2	2.7
Malawi	7	11.8	0.9
Mauritius	93.6	0.1	1.2
Mozambique	6.3	18.6	1.3
Namibia	34	1.4	0.7
Nigeria	46	71.1	60.5
Senegal	33	7.8	3.8
South Africa	70	14	32.6
Sudan	30	25.4	10.9
Tanzania	11	34.2	4.2
Togo	17	5.1	1
Uganda	8.9	24.6	2.4
Zambia	19	9.5	2.2
Zimbabwe	34	8.7	4.5
Other countries	7.6	83.6	6.9
Sub-Saharan Africa	**25.9**	**546.9**	**190.7**
Algeria	98.1	0.6	32.3
Egypt	98	1.5	72.4
Libya	97	0.2	5.7
Morocco	85.1	4.5	25.8
Tunisia	98.9	0.1	10
North Africa	**95.5**	**6.9**	**146.1**
Africa	**37.8**	**553.7**	**336.8**

Region	**1970**	**1990**	**2000**	**2015**	**2030**
North Africa	34	61	90	98	99
Sub-Sahara Africa	9	16	23	33	49
South Asia	14	25	34	43	56
Africa	17	32	41	53	66
Latin America	45	70	87	94	96
East Asia/China	30	56	87	94	96
Middle East	36	64	91	97	99
Developing countries	25	46	64	72	78
World	49	60	73	78	83

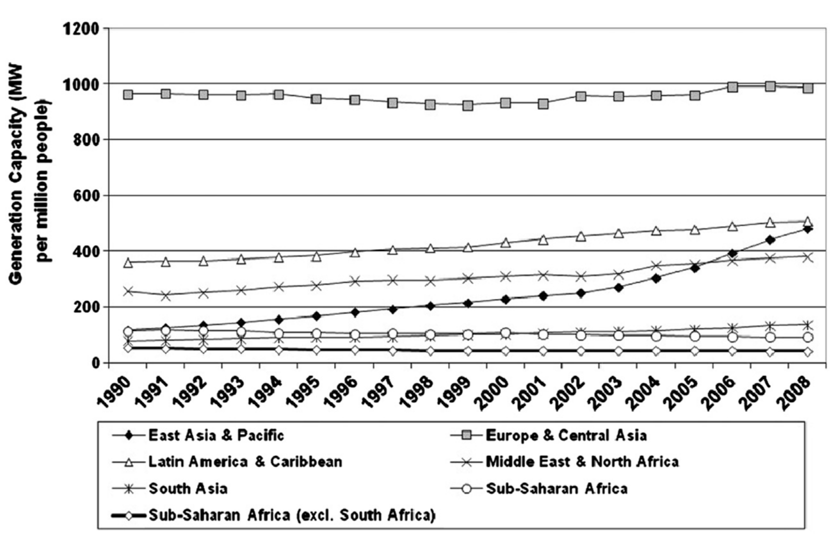

Fig. 2. Electricity generation capacity in SSA and other developing regions [24,25].

Section 5. In addition, the same section states the benefits of RE power sector integration. Finally, in Section 6, integrated challenges affecting RE power sector integration in SSA are analysed.

2. Review of related literature on power sector renewable energy integration

Presently, renewable power generation infrastructures have begun to be progressively integrated into the power sectors of various countries in both developed and developing nations. A reasonable amount of literature has been published recently on renewable electricity production. A study Stambouli [26] comprehensively reviewed the strategic promotion of RE in Algeria for power sector integration, with the emphasis on the market structure, political support and the regulatory and statuary framework. Thiam [16] investigated market price support mechanisms for RE penetration in developing countries for distributed power generation. A tariff incentive for RE technological diffusion was also analysed in this study using Senegal as a case study. Chaurey and Kandpal [27] studied photovoltaic-based decentralised rural energy electrification, with a specific focus on technological barriers, marketing and diffusion challenges, techno-economic analysis and performance evaluation. In Belarus, a study conducted by [28] critically reviewed the RE sector for power production. The paper addressed some background issues related to present and future RE resource consumption in the country, with the main focus on economic transition demands, resource availability and social acceptability.

Community-based energy planning on renewable electricity in Canada was discussed by [29]. Based on the outcome of the study, it was observed that small communities with simple electrical load demands prefer planning their energy structure with multiple RE resources, such as wind, biomass, small hydropower and photovoltaic systems. Voumvoulakis et al. [30] published research on the ability of large-scale integration of RE resources in the Greek power sector to meet the country's energy supply target for 2020. The Indian power sector generates more than one-third of the total GHG emissions in the country, and the situation has compelled the government of India to aggressively promote power sector RE integration [31]. Weisser [32] reviewed the strategic roles of RE technologies for prospective reform in power sector development in small island developing countries. The review discussed drivers and desires for RE power sector integration in territorial islands known for their high dependency on expensive fossil fuels for power generation. The significance of RE integration for electricity consumption is strongly emphasised in many other studies not mentioned here. The need for RE exploitation is now central to developed and developing nations for many reasons, including the following:

- Promotion of regional development, especially in remote locations
- Supplementing the depletion of fossil energy resources
- Opportunity presented by the inexhaustive nature of the resources
- Clean development mechanism for sustainable development
- Endorsement of Kyoto protocol for emissions reductions

3. Renewable energy resources in sub-Saharan Africa

Green energies are clean, efficient and reliable energy systems from long-term RESs, such as wind, sun, water, biomass, biogas, tides and waves, hydrogen and geothermal energy [33,34]. There is significant potential in Africa, particularly the sub-Saharan region, for utilisation of RE, including conventional energy resources. Despite the large amount of energy resources, the socio-economic development of the region has the poorest index compared to any other part of the world. On a global scale, there is mounting agreement that increasing energy access in developing countries is essential to the realisation of the objectives of the Millennium Development Goals [35]. The mandate to make available energy services to the populace has traditionally being entrusted to large-scale, state-owned utilities [36], which are usually associated with overdependence on oil resources and very little with renewables. In summary, Mauritius, South Africa, and Ghana may be mentioned among the foremost countries in SSA that have made significant steps towards increasing their potential for RE consumption [37–39].

3.1. Solar power

Solar energy uses solar radiation of the sun. Solar energy, like other renewables, has significant potential to contribute to the global quest for power sector decarbonisation. Fig. 3 shows the annual average daily solar radiation for Photovoltaic (PV) system utilisation for electric power supply in Africa. As observed, the solar power radiation intensity lies between 3000 and 7000 W/h/m^2, which can be viewed as reasonable when compared to the results of an experiment by [40] that 2324 W/h/m^2/day is sufficient to support average domestic load demands.

Solar energy consumption is currently limited to lighting and the operation of simple appliances (loads) in both rural and urban areas of SSA. Solar-powered water heaters, solar-powered cookers, building integrated photovoltaics and the application of solar photovoltaic distributed electric power generation are limited to just a few countries in SSA. They are more common in countries such as South Africa and Mauritius where there is an increasing tendency to embrace emerging RE technologies in line with the accelerated global pace of RE consumption. Solar energy can provide a suitable electrification alternative to many geographically isolated rural settlements in the sub-Saharan region. Unfortunately, there are very few initiatives for solar energy exploitation in SSA. In Zimbabwe, there is a concerted effort to use solar energy systems for distributed generation of electricity in rural areas under the Global Environmental Facility (GEF) project [42]. In addition to limited financial support from the government, most community-based solar energy projects are either sponsored or supported by donor agencies [43,44]. A few countries, such as South

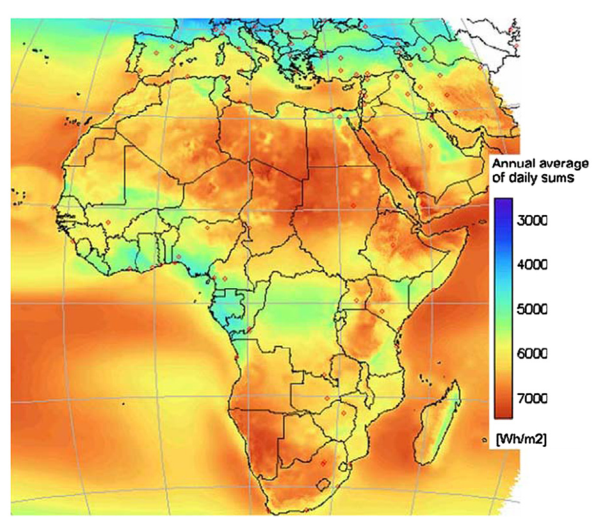

Fig. 3. Annual average of daily sums of solar irradiation in Africa [41].

Africa, Nigeria, Ghana and Kenya, have some local programmes for solar energy utilisation, although there has been little uptake of these programmes thus far. This is because apart from government initiatives for PV street lighting, there are no established financial incentives from the government or from donor agents for massive deployment of home-based PV for electricity in the region. The use of PV in individual homes is very limited due to economic challenges and the general low income of workers in the region.

3.2. Biomass power

Biomass power, also known as bioelectricity, is one of the foremost RESs to attract attention in the struggle for sustainable development. Between 1995 and 2005, the global potential of bioelectricity increased from 104.8 to 183.4 TW h, with an average growth rate of more than 5.8% [45]. Compared to other RE technologies, biomass-based power systems provide more grid quality electricity [46]. RE accommodated 12.9% of world primary energy supply in 2008, with biomass occupying the largest proportion [47]. In SSA, biomass is the largest RE resource [48–50]. Varieties of biomass residues from agriculture, municipal solid waste and forest biomass can be found in sustainable quantities in SSA. Table 2 summarises the potential of agricultural residues for power generation in some selected regions in SSA. Biomass for electricity generation has not been widely exploited in most regions in Africa, except South Africa [50] and Mauritius, both of which use sugar cane in combustion power plants. Biomass consumption in Africa has traditionally been dominated by direct burning of bioresidues for heat energy production, especially for cooking and heating purposes. However, direct burning is associated with a significant loss of useful energy in the form of heat.

The diffusion rate of biomass conversion technologies for electricity in SSA is relatively slow due to a lack of technical knowledge and an insufficient level of public awareness. Nonetheless, different kinds of biomass resources with sustainable potential for power generation are available in SSA. Attention has focused in particular on forest biomass resources for wood fuel and charcoal production. Biogas, which is mainly obtained from varieties of biodegradable waste raw materials, is another promising clean source of energy for cooking and small power generation in rural districts. Although biogas is mainly used for cooking in developing countries, in developed nations it is used for both cooking and power generation. Recently, developing countries have deployed numerous biogas technologies using local raw materials for the construction of digesters. As of 1999, more than 60,000 biogas plants were installed in Nepal [51]. In Bangladesh, 24,000 biogas plants were reported to have been installed by 2005 [52], and about 5000 digesters were installed in Sri Lanka as of 2000 [53]. In terms of biogas use for energy in SSA, the majority of the regional countries have acknowledged the importance of biogas as a replacement for kerosene and LPG. Some ongoing RE energy programmes in the region are strenuously advocating for biogas consumption for cooking. Biogas is a clean methane-rich fuel with low GHG emissions [54–58] when it is burnt for energy use. Records concerning biogas installation in SSA for domestic energy consumption or power generation are not comprehensive due to an ineffective regional data management system. Factors such as inadequate funding, the need for high capital investment, a lack of government support and insufficient knowledge about the technologies and the usefulness of biogas contribute to the retardation in the pace of biogas development and adoption in SSA.

Table 2
Agro residues and power generation potential in Africa [adapted from 51].

Country	Cereal production (MT)	Agricultural residue (MT)	Power potential at 30% availability (MW)
Angola	0.725	0.725	27
Benin	1.109	1.109	42
Burkina Faso	2.902	2.902	109
Burundi	0.280	0.280	11
Cameroon	1.684	1.684	63
Chad	1.213	1.213	45
DRC	1.570	1.570	59
Cote I'Ivore	2.205	2.205	83
Ethiopia	9.280	9.280	348
Gambia	0.213	0.213	8
Ghana	1.943	1.943	73
Kenya	2.730	2.730	102
Malawi	1.843	1.843	69
Mali	2.840	2.840	107
Mozambique	2.007	2.007	75
Niger	2.672	2.672	100
Nigeria	22.783	22.783	854
Senegal	1.085	1.085	41
South Africa	12.352	12.352	463
Sudan	3.643	3.643	137
Tanzania	5.020	5.020	188
Uganda	2.625	2.625	81
Zambia	1.364	1.364	51

DCR: Democratic Republic of Congo.

Bioelectricity generation can offer distributed cogeneration of electricity and heat. This is a common phenomenon in Europe and some other industrialised nations. Bioelectricity facilities are usually located close to the residence of the target consumers to avoid transmission losses, which are commonly encountered in conventional power generation systems. In Africa, electrical power transmission loss is exceedingly high compared to other parts of the world, ranging from two-fold of the global standard of 9.2% in countries such as Kenya, Nigeria, Burundi, Senegal, Tanzania and Congo [51]. To counter this problem, especially in SSA where there is high demand for electricity but the supply situation is constrained, distributed power generation using biomass can be considered a viable alternative. According to [59], issues linked to grid electricity in situations where the demand is high and the supply is low result in poor-quality electricity and increased losses in grid-connected supply. At the biomass generation and distribution level, different countries in SSA have attempted testing various conversion technologies, such as combustion, gasification and pyrolysis, although these are on a very small scale and at an experimental stage. In one initiative, a demonstration project in Uganda used a gasification system for small capacity heat and power generation under the direct supervision of the Ministry of Energy and Mineral Development [60]. At any given place, the main prerequisite for exploring any opportunity for bioelectricity is to conduct an assessment of the feedstock potential to ascertain the energy potential of the available bioresources. Such an assessment is followed by an analysis of the geographical accessibility and the technical availability of the resource to the users.

3.3. Wind power

Globally, wind energy is emerging as one of the most promising alternative sources of energy due to its potential to meet rising demands for electricity [61]. Wherever wind is available with sustainable velocity, it can be explored as a viable alternative for power generation, especially in isolated geographical areas without access to grid electricity. The feasibility of exploiting wind electricity in SSA is rather low compared to solar power, hydro power and biomass. At the biomass generation and distribution level, include insufficient RE technologies, weak capital investment and low wind speed. Many SSA countries are largely land locked and experience low wind speeds [62–65]. Significantly,

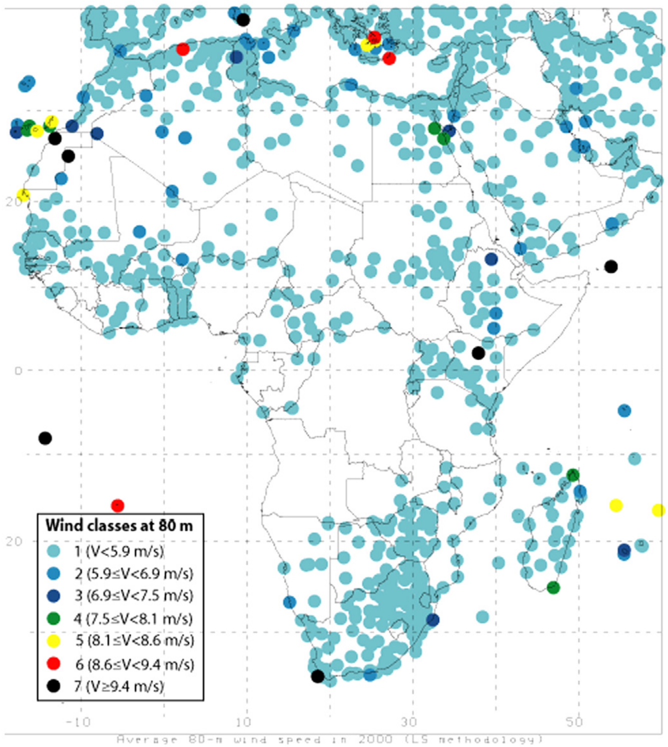

Fig. 4. Wind energy potential in Africa [66].

wind velocity varies from area to area in the different countries and subregions due to variation in topographies and weather conditions. As shown in Fig. 4, a wind speed class 3 (velocity greater than 6.9 m/s) is most suitable for low-cost wind electricity investment. Investment in wind energy could be feasible in the southern part of SSA. Such investment could possibly be in a stand-alone or a grid-integrated system. This level of wind speed or class is more prevalent in Northern Africa rather than in SSA.

Despite the weak potential of wind speed in the sub-Saharan region, many countries have tried operating small-scale wind power systems, with encouraging feedback. For example, in Kenya, more than 220 wind-based operated pumps have been distributed for use in rural locations [67], apart from the 5.1 MW grid-connected wind farms commissioned in the country in 2009 [68]. This means that the development of wind power systems cannot be excluded from the envisaged renewable electricity integration option in the region. Wind power generation is thriving in South Africa, especially in the coastal region of the country. The feasibility of wind electricity has been tested in the northern part of Nigeria. In research conducted by Fadare [69] using an artificial neural network to investigate and predict the distribution of wind speeds across Nigeria, a maximum speed of 13.1 m/s was obtainable in Kano (a north-west regional state). The same study reported a 9.47 m/s maximum annual speed for Jos (a city in north-central Nigeria). In conclusion, the exploitation of wind electricity in other countries in the region cannot be neglected, especially given the desire to expand access to electricity across the region.

3.4. Hydropower

Sustainable kinetic energy can be captured from any flowing body of water, such as a stream, a river or a lake, and converted into electrical energy using a hydroelectric power turbine, which rotates with the aid of the gravitational force of the falling water at a certain height above ground level. Recently, interest in the exploitation of hydropower development [70,71] has dramatically increased across various regions in the world due to escalating global interest in harnessing green energy for sustainable development. In SSA, there are many unexploited natural dams, but just some are presently constructed for electric power generation. Globally, hydroelectricity provides about 16% of the power supply [72]. The development of hydroelectricity could be constrained in the region by factors such as seasonal fluctuations in the volume of water, economic viability, social factors, huge capital investment and p power plant construction time and technical difficulties. These factors have decelerated the pace of hydropower development in SSA. Over 90% of economically feasible potential hydropower sites in SSA are left unexploited [72] due to financial constraints. In Nigeria, over 12,000 MW electrical potential of hydroelectricity exists, but the total installed capacity of hydropower is only approximately 2000 MW. The exploitation of hydropower potential in the entire African region is just 8% [73]. Hydroelectricity is a very promising alternative power supply technology in SSA. Given its numerous advantages listed below, there is a strong need for political and legislative support to foster its exploitation.

- Ability to store energy using a pumped storage system to recycle already used water, thereby making the system less dependent on natural rainfall, which is subject to seasonal fluctuations
- Improves air quality and reduces emissions of GHGs
- Extended useful life span
- High efficiency close to about 80% compared to other renewable electricity
- Affordable operating and maintenance expenses

3.5. Geothermal energy

Geothermal energy is obtained from thermal energy held inside the Earth's crust [71]. Geothermal energy is one of the most promising alternative energy technologies because it can provide a continuous supply of electricity wherever it is needed. One of the great advantages of geothermal power plants is that they can provide power 24 h a day. Geothermal sources of energy are invariable, with no difficulties with intermittent supply compared to other renewable resources, such as wind or solar energy [71]. It is an energy supply technology with proven potential to reduce emissions of GHGs [74]. Developed countries, such as Turkey, Italy and the US, as well as some developing countries, have developed geothermal power for electricity supply. In SSA, Kenya is the only country that has developed a geothermal power plant. Although exploration for geothermal energy resources is ongoing in many other countries in SSA, attempts to use this energy resource where it is available are almost nonexistent due to political factors and weak energy policies.

4. Financial constraints on renewable energy development in sub-Saharan Africa

Major alternative energy sources that exist in sustainable quantities in the entire African continent are solar energy, wind energy, wood biomass and biogas [42]. RE sources potentially provide opportunities to exploit smaller and sustainable energy. Small-scale power generation offers environmentally friendly ways to fulfil local energy needs of remote and rural communities by exploiting the advantages of nearby accessible resources. The diffusion of RE utilisation in SSA has been low due to some critically challenging factors. The vast majority of RE sources in the region have yet to be harnessed, thus making SSA the lowest consumer of modern energy in the world. Among all the

developing regions, SSA has clearly found it difficult to surmount the existing urban–rural energy divide and to exploit the abundant RE resources that exist. Although there is growing interest in expanding the frontier for clean energy development in the region, the absence of financial and infrastructural support remains an obstacle to RE exploitation.

Most African RE forums for carbon reduction essentially support GHG reductions by financial donations from industrialised countries. However many of the developed nations have failed to fulfil pledges to support green energy programmes in developing countries. One expected financial gain by developing countries is to export RE resources such as biochar (charcoal) to other countries within and outside the region, thereby increasing the region's economic potential. As locally available sources of RE are becoming a viable solution to rural energy constraints, developing countries can be expected to overcome energy shortage scenarios with time. However, currently, there is no substantive movement for regional RE integration in SSA. Several countries are seeking an independent means of exploiting their RE capabilities for electricity because the research, development, demonstration and financing of RE in different countries varies according to the socio-political and economic demands of the country. A direct financial gain from RE integration into the regional electricity sector depends upon a progressive approach to financing systems. Effective financial models for RE and environmental protection can adequately guarantee private sector participation and banking system support for market sustainability. Emerging RE funding mechanisms can be strongly supported by tax incentives, feed-in tariffs and mixing subsidies. A combination of these instruments, coupled with other policy frameworks, could favour investments in cheaper RE technologies. It could also foster grid parity RE for bulk energy production at the national level and eventually at the regional scale.

Due to the low population density in rural districts in the region, there is a high cost involved in generating, transmitting and distributing electricity. This financial burden on the government could be reduced by using RE energy in rural areas of SSA, especially as the energy resources are located within these rural areas. For example, woody biomass has been overexploited in the region for wood fuel and charcoal manufacturer. It is widely used in domestic and commercial cooking, thus making small-scale traditional bioenergy systems predominant in the region. In general, there is a poor level of awareness about the utilisation of large-scale bioenergy facilities, such as combined heat and power, combustion and gasification systems. The unsustainable exploitation of forest bioenergy resources in the region has affected the level of carbon stock in the regional forest.

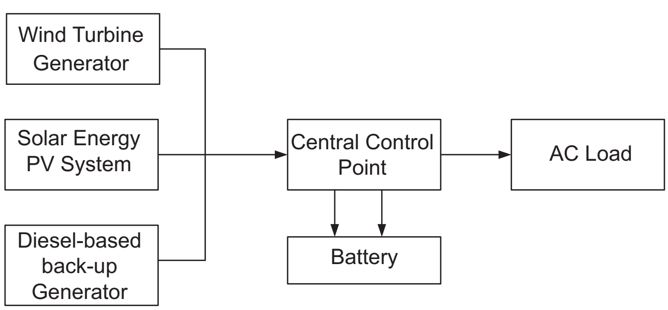

Fig. 5. A Layout of a hybrid power system.

5. A methodology for renewable energy integration and a renewable energy planning and management system

5.1. A suggested methodology for power sector renewable energy integration in sub-Saharan Africa

RE resources for power generation can be utilised either in a single energy supply system or in a combination of different energy systems. The estimation of RE availability in a given area [75,76], together with a conditional assessment of the RE resource [77], determines the methodology for integrating RESs in power generation. The use of more than one RE system for electricity production is called a hybrid renewable energy system (HRES). A

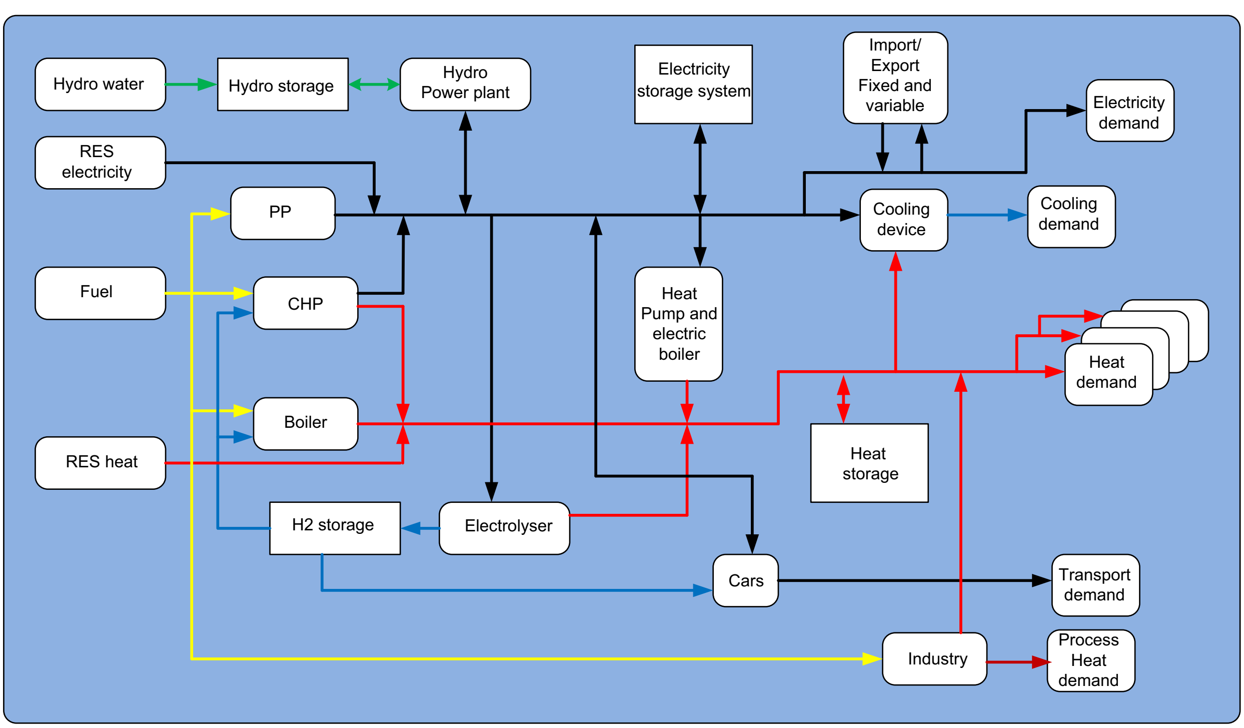

Fig. 6. EnergyPLAN energy system analysis model [85].

HRES can comprise a combination of one renewable and one conventional energy source or more than one renewable, either with or without conventional energy sources working in a stand-alone or a grid-connected approach [76,78]. In SSA, RESs are available in sustainable quantities. However, the majority are intermittent in nature and site specific. A simplified representation of a hybrid power system is shown in Figs. 5 and 6. The implementation of a HRES helps reduce the aforementioned inherent problems with RE. The high tendency for RE intermittency could perhaps be resolved if a diesel generator with a battery-based backup storage system [79,80] was incorporated into the hybrid system. The economic slump in the majority of SSA countries is a major challenge to the implementation of any RE initiative. Adequate planning for RE utilisation through a HRES could reduce the overall investment expenses and hence the cost of energy from renewables for electricity consumers.

5.2. Renewable energy planning and management system

Different RESs require different integration planning approaches because the conversion technologies, the capital cost of investment, the land requirements and, to some extent, the social acceptability and the impacts on the human environment vary from one energy source to another. RE planning and management take into consideration the different sustainable energy resources available in a location. Relying on a single energy resource for a continuous supply of electricity is usually not practical because of the tendency to encounter constraints in supply continuity. Therefore, RE integration planning and management should allow for integrated multiple RE resource consumption. Importantly, this could guarantee the sustainability of RE for decentralised electricity generation, especially for the operation of microgrid power systems.

Furthermore, in any region where the energy supply is not equitable to the demand, resource energy planning to bridge the gap is indispensable. Such planning should take account of the need for a mix of electricity generation systems. Generation planning is a sustainable way of coordinating activities related to energy production to ensure optimal use of energy resources and effective dispatch of the output energy generated. Over 2 billion people still lack an adequate energy supply all over the world [81–84], with the majority residing in SSA. As it is apparent that the energy density of RE resources, with the exception of hydroelectricity, is low, integrated resources planning can be used to mitigate most of the problems linked with the production of RE. The planning must include the choice of energy resource selection, generation technology, cost of logistics and resources availability. In Fig. 5, an energy model called EnergyPLAN model is presented. The model is suitable for RE system power generation analysis, especially for national and regional energy planning schemes. It is an input–output model, which uses data on the capacities and the efficiencies of the energy conversions of the system, the availability of fuels and the RE inputs [85]. With adequate deployment of efficient RE technologies operating at substantial capacities in the region, this model could be adopted to realise RE integration to enable power sector expansion. The model illustrates how different kinds of RESs can be utilised in productive energy generation and how the incorporation of energy storage systems minimises losses, mitigates RE intermittency and provides quality power.

RE can be used in a variety of integrated applications in different sectors. A renewable energy management system can be described as an interactive system, with an effective energy planning and system management aiding the application of the energy resource in various sectors. Planning for RE generation and management requires the involvement of several independent sectors to cater for the diverse needs of energy consumers.

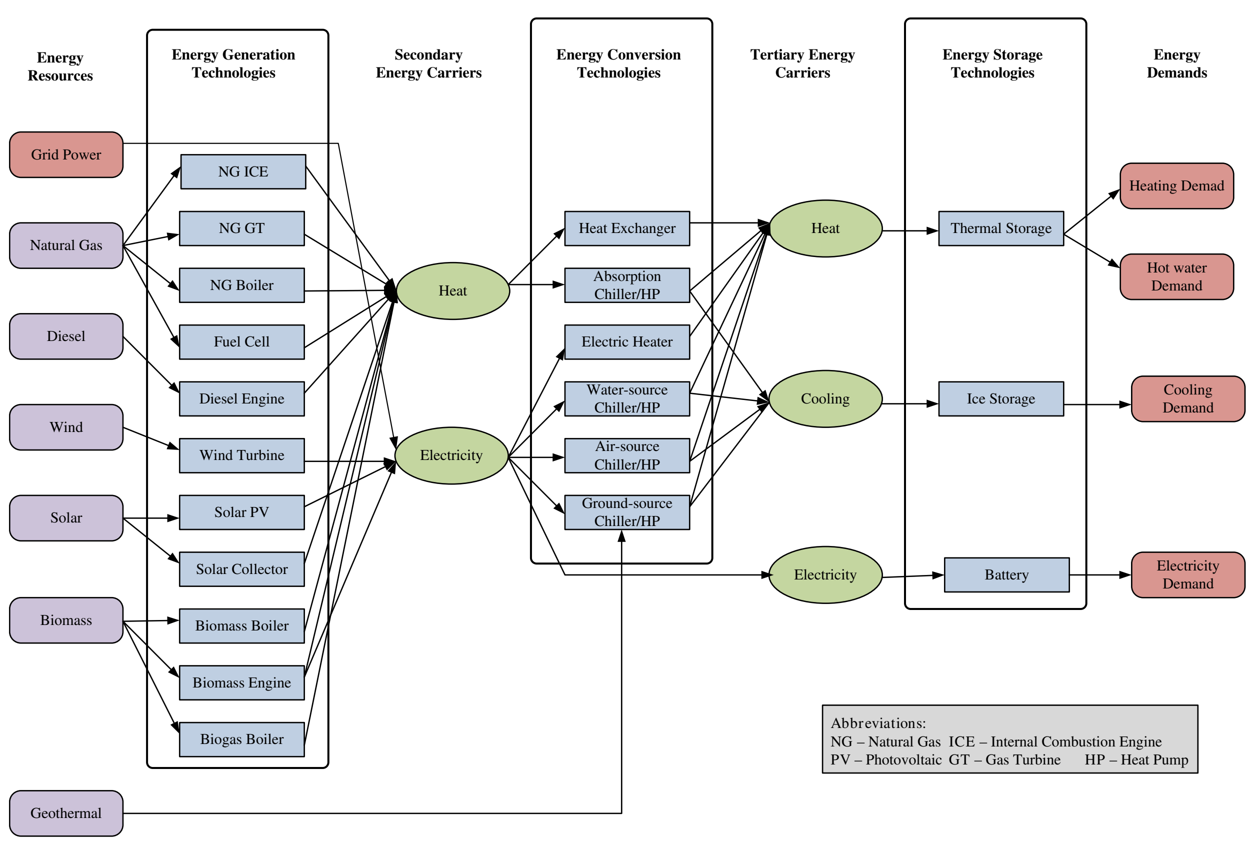

Fig. 7. Superstructure representation of a distributed energy system [104].

A satisfactory RE planning system requires an assessment of the characteristics of the generation system, demand-side management constraints and energy resources supply constraints. As RESs are distributed resources, in planning for RE generation, especially where multiple resources are available, an optimisation technique for the design of the energy production system is crucial. The necessity and the usefulness of an optimal design for a distributed energy production system have been studied by several researchers who focused on the design of integrated RE technologies, including techno-economic analysis and modelling. Most of the modelling systems predominantly concentrated on distributed combined cooling, heating and power infrastructural development [86–95] using different resources such as solar and biomass [96–99]. A more recent model designed for handling problems related to the optimal design of a distributed energy system deals with the superstructural optimal design as presented in Fig. 7. This novel model design explores a mathematical programming approach. It includes several advantages, such as an energy supply chain system [100], an optimal planning design for an energy generation system [101] and infrastructural coordination of a polygeneration energy system [102,103].

Sustainable RE generation, planning and optimisation could also assist in the provision of electricity resource management and the organisation of resource utilisation at community, national and regional levels in developing countries. The distributed generation of energy could play an important role in the provision of electricity to sparsely populated areas. IGERP involving modelling and optimisation would help energy stakeholders to expand access to modern energy in SSA in the following ways:

1. Generation capacity expansion through the exploitation of renewables for energy delivery
2. Limited loss of power produced compared to transmission losses with current conventional power systems
3. Less difficulty with generation control, energy efficiency monitoring and demand-side management

5.2.1. Merits of power sector renewable energy integration planning

5.2.1.1. Meeting the energy demand for sustainable development. Power generation using RESs has strong links with sustainable development in society. When making decisions on the methods of exploiting available energy resources, planners are compelled to cater for human needs. In reality, conventional energy resources cannot be solely relied upon to satisfy human energy needs, especially given that potential global reserves of these resources are decreasing with the progression of time. RESs are long-lasting energy resources with the potential to supplement energy shortages and to reduce levels of GHG emissions. In addition, RESs can be implemented at a realistic cost without causing harmful environmental effects [105–107].

5.2.1.2. Opportunities afforded by increased energy diversity. RESs can enhance the diversity of energy supply options in both developed and developing nations, thereby contributing to the reduction of global and local atmospheric GHGs [105,108]. The diversification of RE resources is also one of the prime measures to guarantee energy security. The ongoing regional interest in SSA including RE sources in electricity generation will increase opportunities for the expansion of energy access in the region. The limited oil resource availability in the region, coupled with constricted financial capacity to purchase oil and gas needed for local energy consumption and for aggressive development, makes the exploitation of RE inevitable. In industrialised countries, RE has been integrated successfully in the energy sector to reduce environmental pollution. In developing countries where energy shortages have had to be confronted, distributed generation using nonconventional RE, such as small-scale solar power, wind power, hydropower and biomass, has been shown to be important, especially in South-East Asia. In countries where the utilisation of RE has been successfully realised, such as Thailand and China, some essential incentives were developed to encourage investors and to increase opportunities for RE diversity.

5.2.1.3. Planning for a community-based renewable energy development scheme. In the design of a community-based energy system, it is essential to ensure that there is a balance between supply and demand scenarios. At the community level, intricate candidate factors must be assessed, adequately planned and technically diagnosed to ascertain the feasibility of the planning mechanism and its socio-economic benefits, including the environmental impacts. In some cases, community-based energy planning schemes have been better equipped to take actions locally and to plan their energy systems autonomously [109,110]. This is the case in areas where RESs are sustainably available for energy consumption. Community-based green energy planning systems usually incorporate a wide range of mental and physical inputs from the citizens. This means that from a wide-ranging perception, the citizens within the target community are important stakeholders with a tendency to drive successful implementation of energy production and consumption. In community energy planning, a community can incorporate energy management into local planning and decision making to fashion community energy plans, which deal exclusively with how local demands will be met, as well as deciding on the supply sources, distribution technology and efficiency enhancements methodology required [29]. It is more ideal for a community without oil resources to plan its energy system production, delivery and consumption with local renewable alternatives. In theory, local-level energy planning is desirable because it addresses the demand and supply of energy by improvements in energy conservation, energy efficiency and switching to RESs [29]. If adopted on a massive scale in a country, this kind of planning can be used to determine the RE agenda at the national and regional level. Unfortunately, there is little emphasis placed on this type of energy planning methodology in SSA. Energy planning processes are not fashioned to accommodate local community stakeholder involvement in decision making, funding or investment. The most important instrument to resolve this problem is to develop a comprehensive and all-inclusive national energy policy, which gives special priority to a wide range of RE actors.

6. Major challenges affecting renewable energy power sector integration in SSA

6.1. Lack of political will

Indisputably, in modern RE planning, political decisions have strong potential effects to influence the present and future share of RESs in the local, national and regional power generation mix. Political decision makers are expected to focus more on market sustainability based on the prevailing economic standard and risk involved. Besides the market structure, technological development and socio-economic impacts are also important. In an atmosphere of good political will for RE development, policies can create new market opportunities and stimulate private sector investment [111]. Energy policies and strategies in SSA have not covered some vital areas. For example, they have not fully addressed the following: planning for basic energy demands, energy security sustainability evaluations, power sector capacity management, environmental protection associated with energy generation and consumption and end user protection through workable tariff settings and monitoring schemes.

Policies regarding energy planning must be consistent with stated objectives. The energy policies of the 27 member states of the European Union address three major concerns: energy security, economic development and environmental sustainability [112]. In addition to the regional and national energy planning policies that exist in some areas, local policies in the European Union states favour RE exploitation to stabilise energy supply trends. Policies are usually stated and implemented by constitutionally empowered decision makers. As a prerequisite, before an energy policy can be implemented for productive and sustainable energy exploitation, feasibility assessments must be conducted. Fundamentally, all energy policies must cover some specific areas of interest, the most important being policy measures, incentives and supports, energy efficiency and conservation, environmental impacts and restrictions, scenarios for energy businesses and suitable technologies.

6.2. Poor financial capital investment

Globally, financial investment in RE production has steadily increased in the last few years due to growing interest in a low carbon economy as shown in Fig. 8. Financial supports for RE is highly influenced by political decisions. Sufficient financial backing for RE can foster a wide range of research and development (R&D) opportunities, which will encourage the growth of new technologies, better conversion efficiencies and cost reductions. Sustainable financial investment for RE development has strong monopolistic tendencies, which could allow growth in the RE subsector. Governments used to be the sole funding agent for RE energy development. However, private investments now largely account for the largest source of financial capital for RE projects [111], especially in developed countries. Germany increased its share of RE in the country's electric power sector from 3.1 to 16.8% between 1990 and 2010 and increased its RE share in the heat energy supply sector from 2.1 to 9.8% during the same period [113]. In China, large-scale financial investment in RE saw the country surpass the United States as the world market leader in wind energy [114]. Incontrovertibly, the largest share of capital investment in global RE development is in Europe, the United States and emerging countries of Southeast Asia. So far, SSA has the poorest financial investment in RE development among all the other subregions in the world. Regional portfolios for RE development are also very weak, taken into account the physical development in RE infrastructures.

6.3. Insufficient research and development guides

Rationally, R&D has to move in line with technological development. Essentially, effective R&D guides for RE development could fast-track the emergence of new and improved RE conversion technologies, innovations and cost reductions, as well as new investment strategies and infrastructural development. As a developing region, SSA is not adequately equipped at present with sufficient R&D directives for RE exploitation. In many countries within the region,

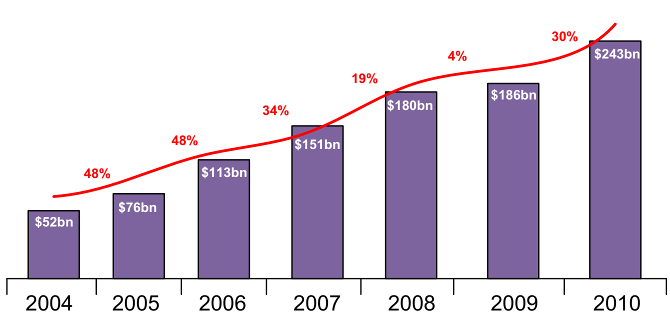

Fig. 8. Global new investment in clean energy 2004–2010. (Includes corporate and government R&D and small distributed capacity adjusted for reinvested equity but not proceeds from acquisition transactions.) [115].

research funds are either not meaningfully allocated, or they are inadequately coordinated. In developed countries and some other developing countries, such as India, China, Malaysia and Thailand, research and academic institutions are directly co-opted into the development of RE due to their technical expertise. Some RE research institutions in such countries are entrusted with the task of database management and technical and economic analyses. To harness RE development in the region, various regional and local research bodies focusing on energy should be obligated by law to be actively involved in RE R&D initiatives. To further energy expansion objectives, the African Energy Commission (Afrec) advocated various measures on global partnerships, the integration of stakeholders, training, information and communication, the exploitation of energy resources and the promotion of a clean development mechanism. Within this structure, a summary of global partnership and stakeholders as advocated by the commission is given by [116,117] as follows:

Global partners

- The International Solar Energy Society
- The World Bank and associated partner organisations
- Development Banks
- Specialised United Nations institutions
- The International Energy Agency
- The European Union
- The Eurec Agency
- The World Wind Energy Association
- Governments
- Industrial and services organisations
- Nongovernmental organisations (NGOs)
- Research institutes
- Universities
- Public services

Stakeholders

- Afrec
- Continental energy organisations
- Local communities
- Innovative NGOs
- National and local governments
- Specialised United Nations institutions
- International organisations concerned
- International bilateral donors affiliated with the countries

6.4. Inadequate training and poor capacity building

The development of the different kinds of RE technologies is still at an early stage in SSA. Therefore, continuous training for capacity building is considered imperative for successful and substantial development of RE in the region. To foster dynamic development of RE, there is a need for suitable technical training. In this regard, energy development personnel need to acquire appropriate knowledge regarding pricing mechanisms, energy demand forecasts, demand-side management, supply distribution technologies, installations and power plant management strategies. Adequate training and capacity building can be ensured through regular training, seminars and workshops, in addition to international collaborations for cross-breeding of technical ideas and interconnections with funding agencies from government ministries, parastatals, departments and, to some extent, NGOs. RE development stakeholders and electricity service providers would be beneficiaries of the training.

6.5. Lack of renewable energy promotion strategies and poor public awareness

In SSA, there is a high level of illiteracy due to the low level of educational diffusion. The development of RE systems in the

region has been hindered by the quality and the quantity of education. More than 60% of people in SSA live in rural communities where there is very little access to electricity. Many households in rural communities have no access to modern mass media, such as television or radios, due to a lack of electricity. Therefore, dissemination of information to the local people is always a very difficult task. To confront this problem, many rural community-based RE orientation programmes will be required to educate the local population about the need to embrace the existing and emerging RE technologies. In addition, there should be programmes tailored towards practical implementation of some viable RE projects, especially on an experimental scale, as Africans tend to have more faith in practical outcomes that they can observe than in theoretical demonstrations.

7. Conclusions

The power sector today has become an indispensable established institution that requires constant expansion due to the rapid increase in human populations and the inevitable dynamics in technological advancement. In developing countries like SSA, there are millions of economically disadvantaged rural communities suffering from a lack of access to electrical energy. There is a likelihood that the prevailing energy crisis in SSA will persist due to poor strategies in energy generation planning and inadequate diversification of energy resources. Integrating RE systems into the power sector of the region will obviously help reduce the threat of a continuous energy deficiency in the entire region, as well as change the regional macroeconomic outlook. Given the potential sustainability of solar, biomass and hydroelectric power resources in the region, small-scale, well-developed electricity generation systems complemented by RE might prevent many energy shortage scenarios in the region if they are affordable and cost effective.

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